The Cartographic Journal *Vol. 52 No. 2* *pp. 95–106* *International Cartographic Conference, Rio 2015 - Special Issue May 2015*

REFEREED PAPER

Cartography-Oriented Design of 3D Geospatial Information Visualization – Overview and Techniques

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In economy, society and personal life map-based interactive geospatial visualization becomes a natural element of a growing number of applications and systems. The visualization of 3D geospatial information, however, raises the question how to represent the information in an effective way. Considerable research has been done in technology-driven directions in the fields of cartography and computer graphics (e.g., design principles, visualization techniques). Here, non-photorealistic rendering (NPR) represents a promising visualization category – situated between both fields – that offers a large number of degrees for the cartography-oriented visual design of complex 2D and 3D geospatial information for a given application context. Still today, however, specifications and techniques for mapping cartographic design principles to the state-of-the-art rendering pipeline of 3D computer graphics remain to be explored. This paper revisits cartographic design principles for 3D geospatial visualization and introduces an extended 3D semiotic model that complies with the general, interactive visualization pipeline. Based on this model, we propose NPR techniques to interactively synthesize cartographic renditions of basic feature types, such as terrain, water, and buildings. In particular, it includes a novel iconification concept to seamlessly interpolate between photorealistic and cartographic representations of 3D landmarks. Our work concludes with a discussion of open challenges in this field of research, including topics, such as user interaction and evaluation.

Keywords: 3D information visualization, 3D semiotic model, cartographic design, user interaction, real-time rendering

INTRODUCTION

Owing to the progress in computer graphics technology, specifically in interactive 3D rendering (Akenine-Möller *et al.*, 2008) and computer graphics hardware, the field of cartography is confronted by new potentials and applications (Kraak, 1989; Buchroithner *et al.*, 2000). The ongoing shift from static media to diverse interactive display technologies has a tremendous impact on the design, production, and use of digital maps and map-related visualization. Today, they are faced with new possibilities to effectively and efficiently present complex, massive 2D and 3D geospatial data. Accordingly, the transfer of existing, proven cartographic principles to modern media and imaging technologies, and the development of new cartographic methods are key challenges for current and future research.

Approaches of interactive non-photorealistic rendering (NPR) (Gooch and Gooch, 2001) applied to 3D geospatial visualization facilitate an effective information transfer (Döllner and Buchholz, 2005). Generally, these techniques comprise various parameterizations to enable a view, data, and user dependent image synthesis. In current literature, a systematic review of recent interactive 3D rendering and visualization techniques, which drive modern display technology, is missing with respect to aspects of cartographic design and map production. Such systematization, however, facilitates the exploration of 3D cartographic design spaces, provides an overview of parameterizations and applications, and enables reference pipelines for visualization to be combined with existing semiotic models.

This paper comprises the following contributions. First, design principles and core variables considered important for an effective design of 3D geospatial visualization are revisited and enhanced in accordance with previous research in semiotics. Second, concepts are provided to map-related cartographic design elements to graphical primitives, based on an analysis of the state-of-the-art in NPR. Third, exemplary illustrative visualization techniques are proposed in correspondence with cartographic design principles of traditional hand-drawn maps (Figure 1) to demonstrate the potentials of computer graphics hardware for real-time rendering and user-defined parameterization. This includes a novel iconification technique for a view-dependent visualization of 3D landmarks.

DOI: 10.1080/00087041.2015.1119462

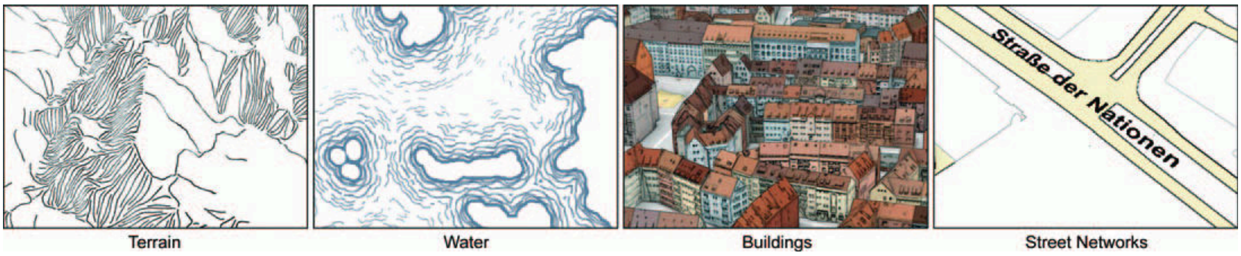

Figure 1. Examples of cartography-oriented design for 3D geospatial visualization

The remainder of this work is structured as follows. The following section revisits the cartographic design process for 3D geospatial visualization and provides an extended 3D semiotic model that complies with the general visualization pipeline. Afterwards, we survey illustrative visualization techniques and propose new techniques for an interactive design of basic feature types (e.g., water, buildings). We then state future challenges for interactive 3D geospatial visualization with cartography-oriented design. The final section concludes this paper. In the following, we refer to all forms of map-related representations of mixed 2D and 3D geospatial information by '3D maps' as a pragmatic notion.

CARTOGRAPHIC DESIGN PROCESS FOR INTERACTIVE 3D GEOSPATIAL VISUALIZATION: AN EXTENDED 3D SEMIOTIC MODEL

An effective communication involves people as recipients and makes the contents relevant within the knowledge transfer (Brodersen, 2008). Geospatial involvement significantly depends on how relevant information is designed and cognitively processed (MacEachren, 1995). Key factors for a successful information transfer involve design aspects that provide a perceivable and comprehensible visualization, and that reduce the memory load of a user by addressing rational, emotional, and cognitive aspects (Kolacny, 1969; Montello, 2002; Fabrikant *et al.*, 2010). Cartographers evolve the collection of visual variables (Bertin, 1983; Tufte, 1983; Brewer, 1994; Garlandini and Fabrikant, 2009) to provide graphic semiology principles and optimize the geospatial information transfer mainly of 2D cartography. Because 3D geospatial visualization, however, adheres to specific challenges, such as occlusion, visual clutter, and the absence of map scales (Jobst and Döllner, 2008b), the need for a 3D semiotic model that includes design aspects for 3D geospatial visualization has received considerable attention in the past years (Häberling *et al.*, 2008; Jobst *et al.*, 2008c; Pegg, 2012). Primary concerns of these works are the mechanisms of independent graphic variables and their mutual impact (Jobst, 2008a). These variables follow the basic stages of 3D map production, such as modeling, symbolization, and visualization (Häberling, 1999; Häberling *et al.*, 2008), including psychological and physiological design aspects (Albertz, 1997; Buchroithner *et al.*, 2000).

Researchers agree that the cartographic design process should account for application space, level of interactivity, and the audience of purpose (Hake *et al.*, 2002), including the user's context and environment, skills, and competence, and the purpose of visualization (e.g., user's task) (Nivala and Sarjakoski, 2003). User interaction plays an important role in 3D geospatial visualization to consider these contextual constraints, as it provides the means to adapt the spatial and thematic granularity at which 3D model contents should be represented (i.e., the level of abstraction, LoA) (Semmo *et al.*, 2012b). In practice, this results in user-defined parameterizations of 3D semiotic variables, ranging from high-detail definitions (e.g., using unfiltered data) over symbolized (Häberling, 1999) to completely abstract definitions (Kraak, 1989; Dykes *et al.*, 1999). Because the presentation of 3D contents in perspective views can be manifold and complex; however, 3D objects need to be generalized to display relevant information in a clear and efficient manner (Petrovic, 2003; Häberling *et al.*, 2008). In cartographic theory, a coupling of the 3D semiotic model to a well-established framework that supports user interaction and generalization has not been formulated. From a computer graphics perspective, however, this is mandatory to provide the conceptual means for a hardware-accelerated visualization process.

We extended the 3D semiotic model to comply with the visualization pipeline of 3D computer graphics (Ware, 2004), which is a generally accepted model by visualization researchers and practitioners. Figure 2 categorizes variables of the models by Jobst *et al.* (2008c) and Häberling *et al.* (2008) in five processing stages, with additional interaction aspects for user involvement and generalization operators for an automated design. The model also considers temporal and spatial coherence of graphical elements as important design aspects, along with preserving (monocular) cues for humans to infer depth (Surdick *et al.*, 1994; Pfautz, 2000; Buchroithner *et al.*, 2000). In particular, the shower-door effect should be avoided at the rendering stage, i.e., the impression that a 3D scene is observed through a semi-transparent layer of (texture) marks (Bénard *et al.*, 2011).

Our model embeds cartographic generalization operators that are used to transform geodata into human-readable maps (Sester, 2007; McMaster and Shea, 1992; MacEachren, 1995). The transformation and presentation techniques are based on combinations of generalization operators, such as class selection, simplification, enhancement, displacement, or typification (Foerster *et al.*, 2007). Generalization operators can be applied (1) to the original geodata of a 3D virtual model in the filtering stage, leading to a generalized primary landscape model, (2) to the mapped data in the mapping stage (symbolization) to yield a generalized cartographic model, and (3) in the rendering stage for a generalized graphics representation. In practice, concrete visualization techniques use a combination of these operators. In particular, generalization operators for all three stages are required if they have to provide adaptive,

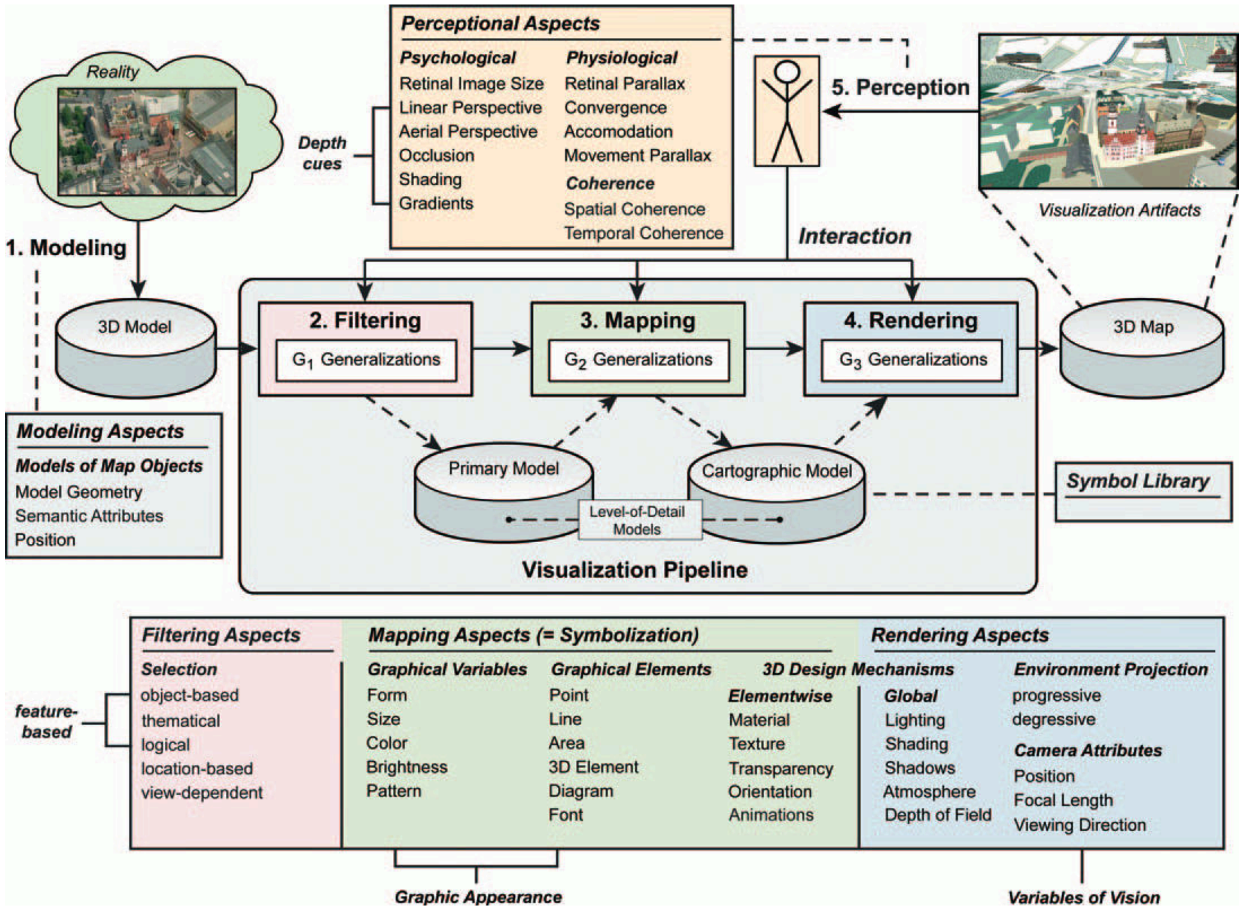

Figure 2. Extended 3D semiotic model that integrates the design aspects of Jobst *et al.* (2008c) and Häberling *et al.* (2008) into the general visualization pipeline (Ware, 2004), coupled with concepts for cartographic generalization (Foerster *et al.*, 2007). The visualization process comprises five processing stages: (1) modeling of real-world phenomena (features), (2) filtering and pre-processing, (3) mapping of the primary model to a cartographic model via symbolization, (4) rendering, and (5) the perceptional interface

dynamic generalized models for interactive 3D systems that conform to graphic semiology principles.

User involvement is a critical design aspect to maintain an iterative feedback loop between the visualization system (as design instance) and the user's requirements (as consumer) (Buchroithner *et al.*, 2000; Peterson, 2005). A good interactive design presents as much information as required for context (Reichenbacher and Swienty, 2007). In particular, the filtering stage provides an effective user interface to select only that information required for further processing. Figure 3 provides examples of focus and context definitions for the visualization of virtual 3D city models.

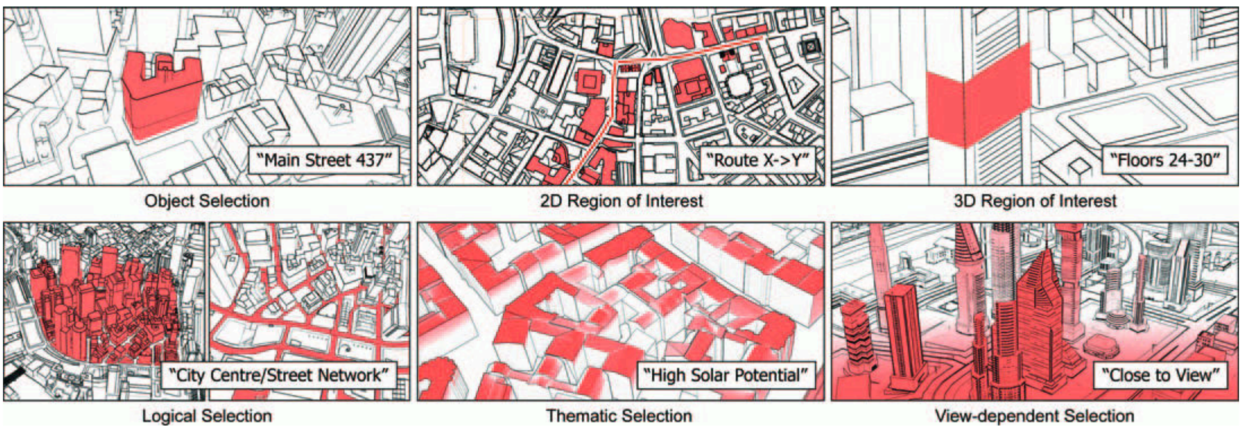

Figure 3. Exemplary filtering functions for focus and context definitions

Table 1. Visualization techniques for 3D cartographic design spaces, sorted by year and primary model data (terrain [T], water [W], green spaces [V], buildings [B], transportation [S], general [G])

			Filtering			Mapping (Symbolization)									Rendering			Perception			
	Publication	Model Data	Feature-based	Location-based	View-dependent	Graphical Variables	Graphical Elements	Colour	Font	Material	Texture	Transparency	Orientation	Animation	Lighting	shading/ shadows	Environment Projection	Psych.	Phys.	Coherence	User Interaction
Terrain Design	Yoeli (1985)	T				x	x				x		x			x					
	Dowson (1994)	T			x	x	x								x	x		x			x
	Kennelly and Kimerling (2000)	T				x	x						x			x					
	Hurni *et al.* (2001)	T				x	x				x				x	x					x
	Jenny (2001)	T	x			x									x	x					x
	Kennelly and Kimerling (2001)	T		x		x	x	x								x					
	Lesage and Visvalingam (2002)	T			x	x	x											x			x
	Whelan and Visvalingam (2003)	T			x	x	x											x			x
	Buchin *et al.* (2004)	T	x	x		x	x				x		x		x	x				x	x
	Bratkova *et al.* (2009)	T	x			x	x	x			x		x		x	x	x	x			
	Degener and Klein (2009)	T															x	x			
	Kennelly (2009)	T				x		x							x	x		x			
	Glander *et al.* (2010)	T		x		x	x	x						x		x					x
	Jenny *et al.* (2010b)	T				x	x									x		x			x
	Leonowicz *et al.* (2010)	T				x										x		x			x
	Mower (2011)	T	x	x		x	x				x		x		x	x				x	x
	Kennelly (2012)	T				x	x				x		x			x					
	Deng *et al.* (2013)	T			x												x	x		x	x
	Samsonov (2014)	T				x	x	x			x		x			x					x
W	Semmo *et al.* (2013)	W	x	x	x	x	x	x	x		x		x	x		x		x		x	x
V	Deussen and Strothotte (2000)	V			x	x	x									x		x		x	x
	Coconu *et al.* (2006)	V			x	x	x									x		x		x	x
Building Design	Döllner and Walther (2003)	B	x		x	x	x	x		x	x		x			x					x
	Döllner and Buchholz (2005)	B	x		x	x	x	x		x	x		x			x		x			x
	Elias *et al.* (2005)	B	x			x	x	x	x				x					x			
	Glander *et al.* (2007)	B	x		x	x	x	x		x						x					x
	Grabler *et al.* (2008)	B/S	x	x		x	x	x	x	x			x				x				x
	Qu *et al.* (2009)	B/S	x	x		x	x		x									x			x
	Hirono *et al.* (2013)	B/S	x	x	x	x	x											x			x
	Jahnke *et al.* (2013)	B	x			x	x	x			x		x								
Vector Data	Kersting and Döllner (2002)	S/T	x			x	x	x	x		x							x			x
	Wartell *et al.* (2003)	S/T				x	x	x									x			x	x
	Takahashi *et al.* (2006)	S/T	x		x												x	x		x	x
	Schneider and Klein (2007)	S			x	x	x	x				x				x	x				x
	Vaaraniemi *et al.* (2011)	S			x	x	x	x			x	x						x			x
Labeling	Bell *et al.* (2001)	G	x		x	x	x		x				x					x			x
	Götzelmann *et al.* (2005)	G	x		x	x	x		x				x					x		x	x
	Maass and Döllner (2006)	G	x		x				x				x				x	x			x
	Ropinski *et al.* (2007)	G	x		x	x	x		x				x			x		x			x
	Cipriano and Gleicher (2008)	G	x		x	x	x		x				x					x			x
	Maass and Döllner (2008)	G	x		x				x				x				x	x			x
	Vaaraniemi *et al.* (2013)	G	x		x	x	x	x	x				x					x			x
	Vaaraniemi *et al.* (2014)	G	x		x			x	x				x					x		x	x
MPVs	Lorenz *et al.* (2008)	G										x					x	x			x
	Jenny *et al.* (2010)	G															x	x			x
	Jenny *et al.* (2011)	G		x	x												x	x			x
	Jenny and Jenny (2013)	G	x			x					x		x		x	x	x				
	Pasewaldt *et al.* (2014)	G	x	x	x	x	x	x			x	x	x	x		x	x	x		x	x
Focus + Context	Trapp *et al.* (2008)	G	x	x		x	x	x		x						x		x			x
	Glander and Döllner (2009)	G	x	x	x	x												x			x
	Trapp *et al.* (2010)	G	x	x	x	x	x	x			x	x				x		x			x
	Semmo *et al.* (2012a)	G	x			x	x	x		x	x	x				x		x			x
	Semmo *et al.* (2012b)	G	x	x	x	x	x	x			x	x	x	x		x		x		x	x
	Engel *et al.* (2013)	G	x	x		x		x			x				x	x		x			

ILLUSTRATIVE VISUALIZATION TECHNIQUES

This section surveys illustrative visualization techniques according to the extended 3D semiotic model, and proposes new techniques based on building blocks of the real-time rendering pipeline.

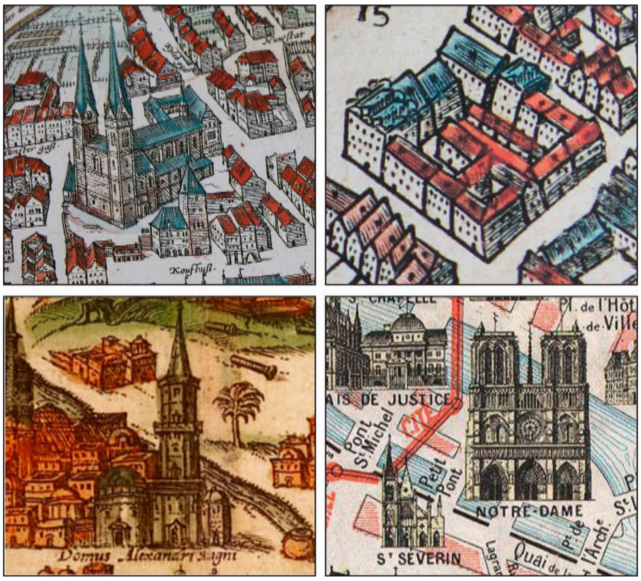

Figure 4. Examples for the cartographic design of buildings

Taxonomy and overview

Non-photorealistic rendering is a particular domain of computer graphics that has been adopted and used in illustrative visualization to provide the hardware-accelerated means for reducing visual complexity and directing a viewer's focus of attention to features of interest (Gooch and Gooch 2001; Santella and DeCarlo, 2004; Cole *et al.*, 2006). Table 1 presents a non-exhaustive overview of visualization techniques that consider cartographic design aspects in 3D spaces. This overview is drawn with respect to the extended 3D semiotic model (Figure 2), and is categorized by feature type semantics using the taxonomy of CityGML (Kolbe, 2009). From our research, we conclude

- Terrain: we distinguish between techniques for contour highlighting, simulation of traditional illustrations by means of slope lines and hachures, hill shading and relief shading, and isolines. Perceptional design aspects have also been explored using progressive or degressive projections via multi-perspective views (MPVs) to handle occlusions.
- Water: a first extensive framework for 3D geospatial visualization has been presented by Semmo *et al.* (2013) to simulate waterlining, contour hatching, water stippling, and labeling at different LoAs.
- Green spaces: vegetation objects can be distinguished without and with individual characteristics (Döllner and Buchholz, 2005), the first being based on 2D distribution functions via synthesis of point patterns

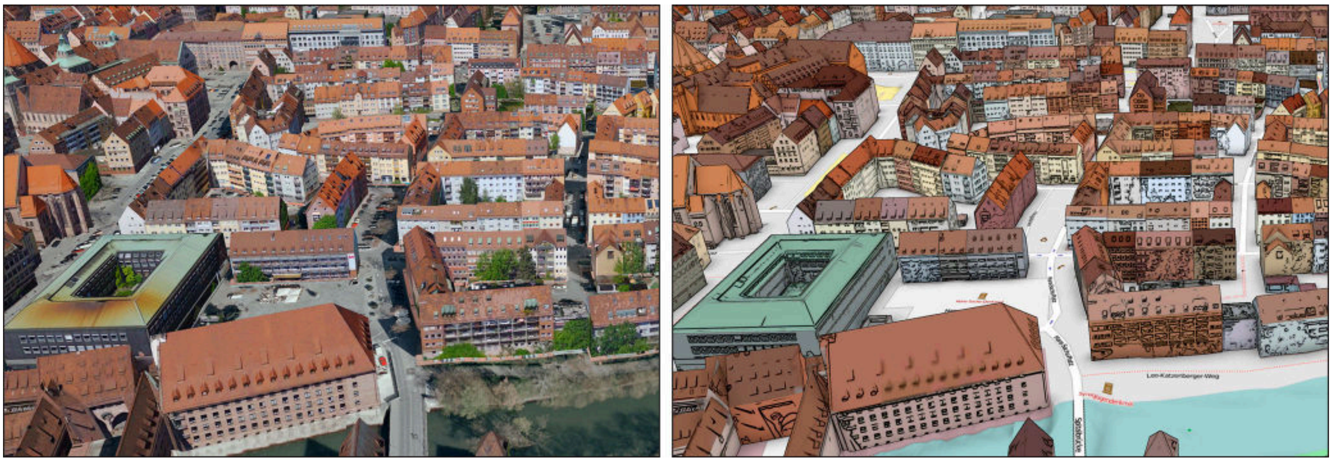

Figure 5. Abstraction of 3D building models for the city of Nuremberg (Germany)

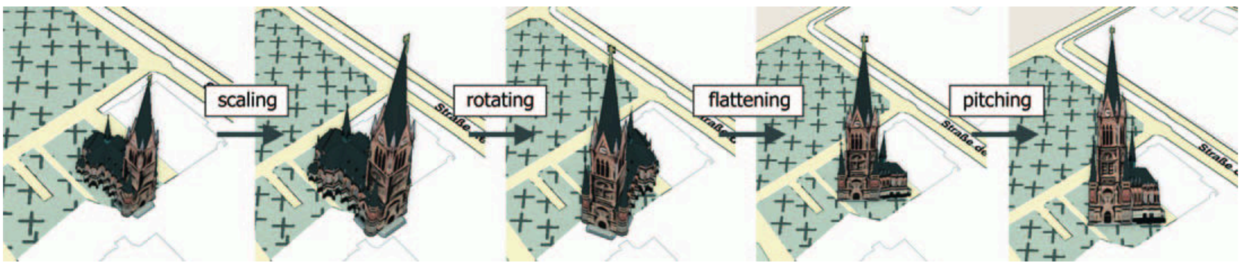

Figure 6. Our iconification technique view-dependently transforms 3D landmarks

(e.g., Jenny *et al.*, 2010a) and element arrangements (e.g., Hurtut *et al.*, 2009) for symbolization, and the latter being based on individually stylized 3D objects (e.g., trees, Deussen and Strothotte, 2000).

- Buildings: techniques for 3D building design are often based on reduced colour palettes with typified or stylized façade elements, and symbolized LoA representations (e.g., for tourist maps, Grabler *et al.*, 2008).
- Transportation networks: their projection on digital terrain models (draping) and disocclusion can be identified as a key challenge (e.g., Takahashi *et al.*, 2006), together with colorization and view-dependent contour-lining in 3D perspective views (e.g., Vaaraniemi *et al.*, 2011).

Many visualization frameworks are also coupled with generic NPR techniques (Kennelly and Kimerling, 2006), e.g., the depiction of suggestive contours to convey shape (DeCarlo *et al.*, 2003), edge-preserving image filtering for LoA visualization (Semmo and Döllner, 2014), and labeling. Most of these techniques can be applied in real-time using image-based rendering concepts (e.g., G-buffers) (Saito and Takahashi, 1990). Focus + context visualization is a relatively new field of research; previous work use location-based or view-dependent metrics (Semmo *et al.*, 2012b) to select and to combine different LoAs according to user interaction and semantics.

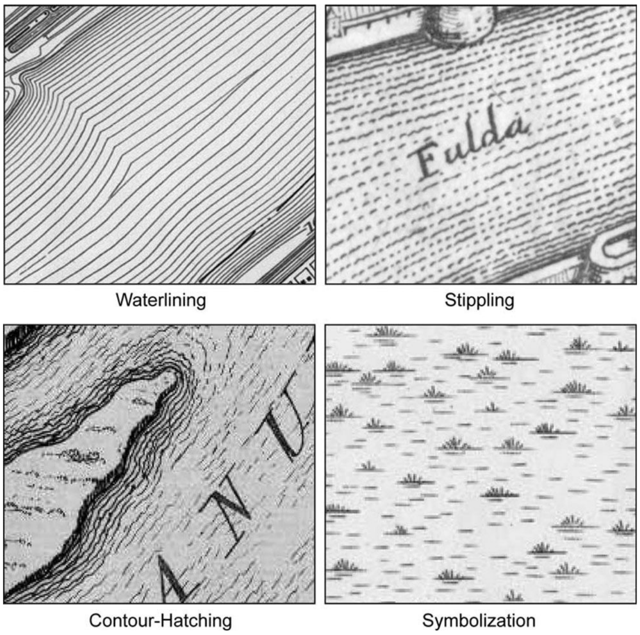

Figure 7. Examples for the cartographic design of water surfaces

Visualization techniques for basic feature types

We empirically analyzed illustration techniques by famous cartographers printed in map collections (e.g., Merian, 2005), and textbooks on map design (Imhof, 1975; MacEachren, 1995; Kraak and Ormeling, 2003; Tyner, 2010). Based on this research, this section presents visualization techniques for buildings, water surfaces, green spaces, transportation networks, and digital terrain models. The main focus lies on how design principles used for traditional hand-drawn maps can be implemented with buildings blocks of the real-time rendering pipeline, such as texturing and deformation, to demonstrate the capabilities of modern computer graphics hardware.

Building and site models

Four graphical core variables for buildings and sites can be extracted (Figure 4). (1) Reduced colour palettes are often used for visualization, e.g., using distinct colours for roofs and façades to distinguish between sacred and secular buildings. (2) Contour lines are often depicted to better distinguish building instances. (3) Building features are depicted using strokes, for instance, to indicate windows. (4) Important buildings may be shown from a "best view", i.e., a landmark is rotated to face its most characteristic façade; this concept is often practiced in the design of tourist maps.

We implemented an algorithm that automatically extracts dominant colours (colour palette) and structural elements (variations in colour value/intensity, such as window contours) from photorealistic textures, such as aerial images. Previous work showed that these contour edges may improve depth perception significantly, e.g., in the visualization of thematic data (Engel *et al.*, 2013). To summarize, two major steps are performed:

Colorization: Dominant colours are derived from textures in regions with constant colour tone, which are weighted via entropy-based metrics. Afterwards, the algorithm by Levin *et al.* (2004) is used to obtain (re-)colourized façades, e.g., in the style of natural colour maps (Patterson and Kelso, 2004).

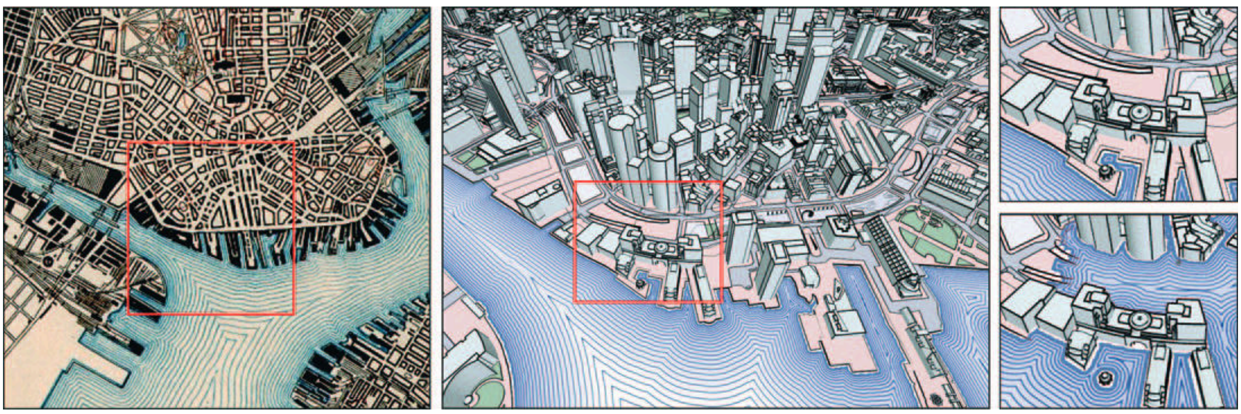

Figure 8. Left: Boston Harbor, 1903 (from Historic USGS Maps of New England and NY), right: our method applied to a virtual 3D model for flooding simulation

Contour Lines: Difference-of-Gaussians filtering is performed on each scene texture (Semmo and Döllner, 2014), coupled with an image-based approach (Nienhaus and Döllner, 2003) for enhancing contour lines.

Figure 5 exemplifies a result of our algorithm applied to a virtual 3D city model. Compared to typical photorealistic depictions, our method is able to improve feature contrasts and express uncertainty.

We also implemented a visualization technique that uses deformations to automatically transform 3D buildings and sites to iconified variants according to their best views. For buildings, best views often face the main entrance and can be approximated via viewpoint entropy (Vázquez *et al.*, 2004), or explicitly defined via model semantics. To obtain a transformed landmark in world space coordinates, the following four steps are performed on a per-vertex basis at the rendering stage in real-time (Figure 6):

1. Landmarks are non-linearly scaled to improve their visibility in far view distances (Glander *et al.*, 2007). A weighted smoothstep function is used to compute the scale factor.
2. Landmarks are pitched so that their best-view direction horizontally coincides with the user's view direction.
3. Landmarks are flattened in depth; i.e., their geometry is projected to the plane facing the horizontal view direction (billboard synthesis).
4. The billboard representation is yawed by the camera elevation to vertically face the view direction.

The linear combination of all steps yield transformed positions of a 3D landmark. In addition, a smooth interpolation between the original 3D representation and iconified version can be performed as an animated transition. Here, view metrics may be used to parameterize this interpolation (e.g., view distance) for focus + context visualization (Semmo *et al.*, 2012b).

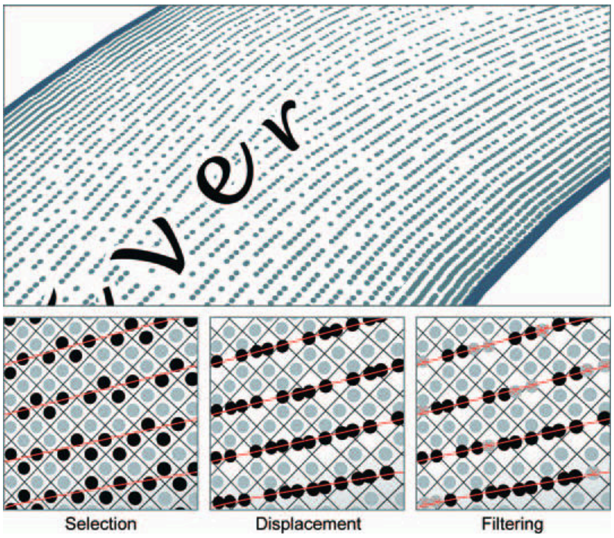

Figure 9. Synthesis of water stipples

Water surfaces

Illustration techniques for water surfaces are diverse (Figure 7). A popular technique in the first half of the twentieth century for lithographed maps was waterlining, i.e., the placement of fine solid lines parallel to shorelines, where the spacing between succeeding lines gradually increase. Another conventional technique for hand-drawn maps is water stippling, where distance information is propagated by small dots, aligned with non-linear distances to shorelines. Contour hatching has been widely used to establish motion, i.e., placing excessively wavy strokes with high-density near shorelines, complemented by loose lines with increasing irregularity towards the middle stream. Other illustrations use non-feature-aligned cross-hatches for land-water distinction, but have been replaced in the second half of the twentieth century by colour tones and drop shadows. The techniques may be complemented by an irregular placement of signatures with area-wide coverage.

Waterlines correspond to shaded areas of a water surface with equal shoreline distance. To comply with non-equidistant interspaces, a non-normalized distance map is computed and used to independently apply waterlining from a water surface's scale (e.g., oceans vs lakes). This automatically derived map is used to query the distance to the nearest shoreline for each point on a water surface, and thus, is able to effectively convey shape. The correspondent distance values are then thresholded using a non-linear step function, and padded by small intervals to render antialiased waterlines with smooth transitions. For a continuous level of abstraction, the thresholding is parameterized by the view distance. At high-view distances, this approach significantly reduces the number of rendered waterlines and provides a smooth transition while zooming

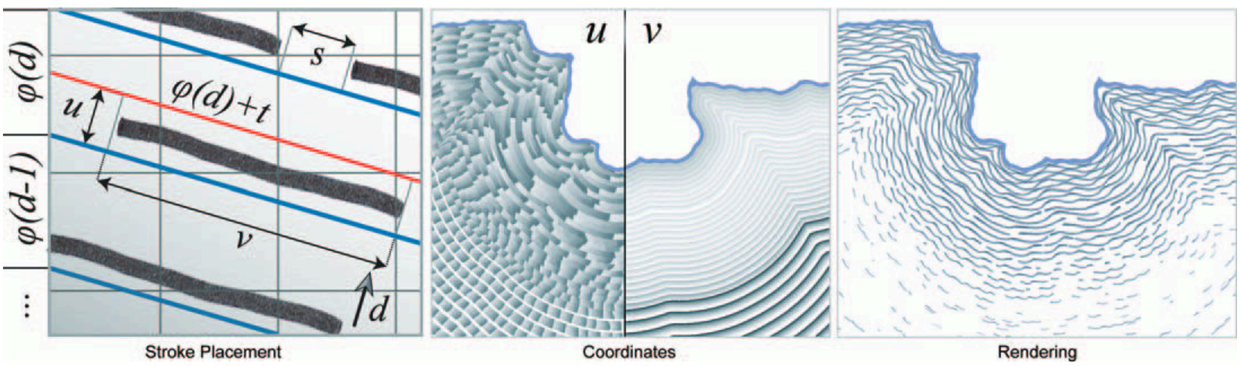

Figure 10. Using distance maps to automatically perform contour hatching

in a 3D scene. Figure 8 shows a rendering result that uses our waterlining technique to illustrate the land–water interface in a dynamic flooding scenario.

We employ an enhanced variant of Glanville's (2004) texture bombing to place water stipples with feature-aligned distribution and irregular density, i.e., to convey shape and motion. The basic idea is to randomly place glyphs in regularly distributed grid cells. We extend this algorithm by three phases; a selection, displacement, and filtering of stipples (Figure 9). Instead of using a random placement of these stipples, offsets are computed that align them with the waterlines.

Finally, we developed a novel contour-hatching technique to symbolize water movements. Once a feature-aligned distance map is computed, digitized stroke maps are irregularly placed with non-linear distance to shorelines. Parameters for stroke length, thickness, and spacing are defined and applied during rendering to provide artistic control over this placement. Here, the main idea is to derive and threshold 2D texture coordinates for each rendering fragment by bilinearly sampling distance maps (Figure 10). Because this placement works in object space, it provides frame-to-frame coherence, and avoids the shower-door effect known from image-space techniques. In addition, water movements can be animated quite easily, contrary to static media, e.g., by shifting individual strokes along the major directions of the computed distance maps.

Green spaces

Green spaces are often depicted in perspective views on entity level using detailed graphics, or via symbolization (Figure 11). The first approach can be modeled via example-based methods and instancing, while for the latter we again use texture bombing (Glanville, 2004). The approach aligns and scales the signatures with the view direction and distance during shading to reduce visual clutter (Figure 13a). The symbols can be parameterized to reflect land-use information (e.g., arable land, grassland) and tree species.

Transportation networks

Two general approaches for the depiction of transportation networks exist: (1) non-explicitly by the principle of surroundedness (MacEachren, 1995) (Figure 12a) and (2) the explicit graphical depiction via connected route segments (Figure 12b). In modern maps, contour lines often surround fine-textured fills or solid colours to add visual contrast and improve the figure-ground perception. We implemented a shading-based technique that models this behavior using distance maps to generate and stylize route geometry on-the-fly during rendering (Figure 13b). The technique enables interactive modifications of the depicted content (e.g., localized colour schemes, view-dependent stylization for focus + context visualization). Further, it uses qualitative colour schemes to portray different grades of roads and enables cognitive grouping of each network type (Kraak and Ormeling, 2003), where primary streets often overlap secondary or tertiary streets. This approach provides a highly flexible stylization, since no pre-computations are required, which is vital for highlighting important or prioritized route segments in dynamic visualization scenarios.

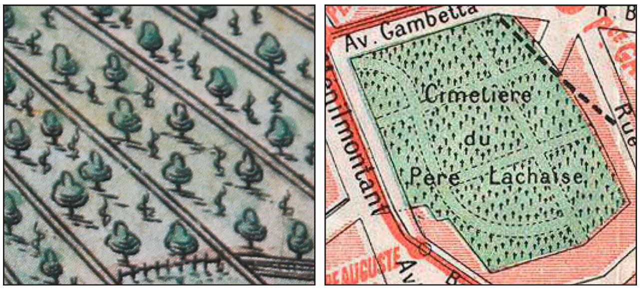

Figure 11. Examples for the cartographic design of green spaces

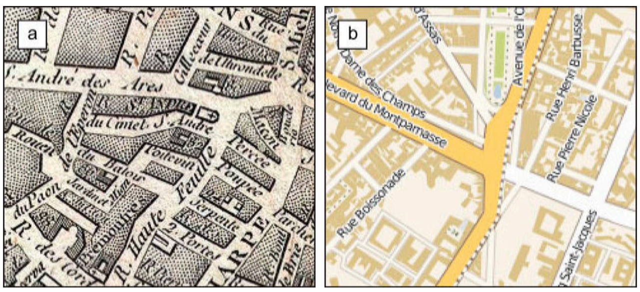

Figure 12. Examples for the cartographic design of street networks: a) non-explicit vs b) explicit graphical representation

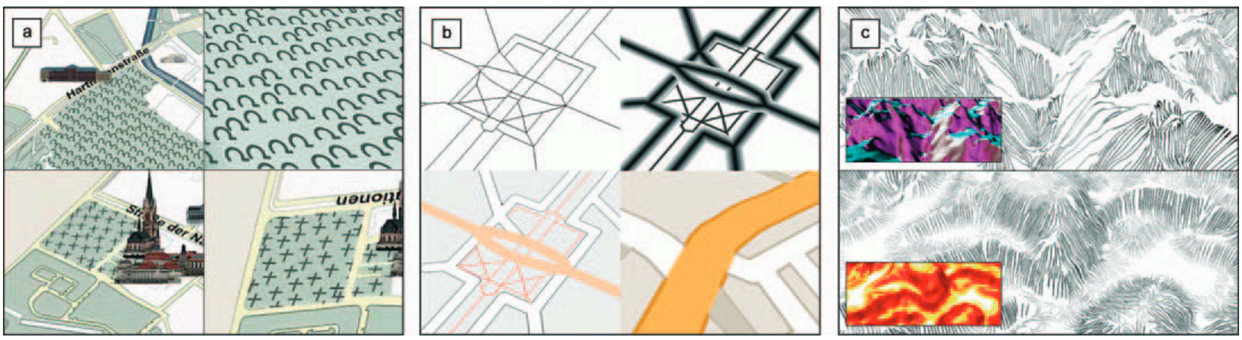

Figure 13. Results for a) green spaces, b) street networks, and c) digital terrain models. The stylization (e.g., colour theme, stroke thickness, glyph size) is parameterized during rendering to enable a user-defined or view-dependent design process

Digital terrain models

At this point, we do not add on the substantive literature on terrain design and visualization. A reasonable shading-based approach for hatching is to extract morphometric variables from height fields (e.g., slope steepness), and then trace and stylize slope lines at the rendering stage via an example-based shading approach (e.g., placing digitized strokes). Figure 13c depicts two results following the methods of Buchin *et al.* (2004).

DISCUSSION

The presented systematization of rendering and visualization techniques via the extended 3D semiotic model form a basis for the development of more advanced visualization concepts, tools, systems, and applications, i.e., to embed cartographic design into 3D geospatial visualization. The presented illustrative visualization techniques demonstrate the parameterization capabilities of modern computer graphics hardware to simulate selected design principles found in hand-drawn maps. An elaborate study of their practical use in real-world scenarios, however, remains subject to future work.

There are numerous technical and conceptual aspects for further improvements of the presented results. Despite algorithmic optimizations and feature enhancements to ongoing developments in computer graphics hardware, the parameterization and configuration of the visualization techniques to non-expert users comprises a number of potentials for future research. In particular, this includes the question on how the parameterization of visualization techniques can be adapted to the virtual camera to ensure optimal results for different viewing situations.

Further, the development of dedicated interaction techniques based on direct user input (e.g., via touch technology on mobile devices) and according to feature semantics is required to effectively control the visualization parameters, and thus, foster further applications in map production pipelines. Focus + context and zooming interfaces are promising concepts to provide these constraints in 3D geospatial visualization, especially considering an interactive filtering process. Although some of the presented techniques are already included in software systems used by non-experts, the conduction of qualitative and quantitative user studies remains an important topic for future works to further improve the visualizations techniques.

Furthermore, most of the techniques considered in this paper are designed to handle outdoor visualization scenarios. With respect to this, the presented systematization can be extended to cover indoor mapping scenarios as well. Based on CityGML LoD-4 models (Kolbe, 2009) or building information model standards, this can include combinations of ghosting, cut-away, and explosion viewing techniques to support and to complement computer-generated camera paths, and guarantee that a user is able to preserve the spatial context during navigation.

Finally, a major research direction represents the transfer and integration of visualization techniques into service-oriented architectures to facilitate their application for cloud computing and mobile devices. Integration into these infrastructures enables a broad and scalable access of geospatial data, e.g., using new specialized mapping services or a combination of existing ones (Beaujardiere de la, 2006) to foster the availability and accessibility of geospatial products and applications.

CONCLUSIONS

We present an overview of new approaches to the cartography-oriented design of map-related representations as well as a correlated extended 3D semiotic model that integrates cartographic design aspects and concepts of generalization into a reference visualization pipeline, including new aspects, such as filtering and coherency, to help systemizing the exploration of 3D cartographic design spaces. Using this model, we give an overview on the state-of-the-art in the visualization of 3D geospatial information based on 3D semiotics and NPR. On top of this, we present exemplary visualization techniques for basic geographic feature types and how core mechanisms of the modern real-time rendering pipeline can be leveraged, such as texturing and shading. Most notably, these techniques demonstrate the capability to shift the design process from pre-processing to all interactive stages of the visualization pipeline, which is promising for digital web based and mobile mapping services to provide an accomplished context-aware visualization – e.g., sensitive to the environment and purpose of visualization (user's task). Future work will have to show how convenient the proposed visualization techniques are in real-world scenarios, such as routing or geospatial exploration.

BIOGRAPHICAL NOTES

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ACKNOWLEDGEMENTS

The Nuremberg 3D city model is used by courtesy of the City of Nuremberg, Bavarian Agency for Surveying and Geoinformation (2013). The authors would also like to thank our technology partner 3D Content Logistics. This work was funded by the Federal Ministry of Education and Research (BMBF), Germany, within the InnoProfile Transfer research group '4DnD-Vis' (www.4dndvis.de). Image Credits: Figure 4/11: Braun/Hogenberg – "Städte der Welt" (2011), Robelin – "Paris Monumental et Metropolitain" (1932), Figure 7: Matthaeus Merian – Topographia Germaniae (2005), U.S. Geological Survey – "Map of New Orleans" (1891), Figure 12: Louis Brion de la Tour – "Paris" (1787), tripomatic.com – "Tourist map of Paris" (2012).

REFERENCES

Akenine-Möller, T., Haines, E. and Hoffman, N. (2008). **Real-Time Rendering**, AK Peters, Natick.

Albertz, J. (1997). Wahrnehmung und Wirklichkeit – Wie wir unsere Umwelt sehen, erkennen und gestalten, Band 17 der Schriftenreihe, Freie Akademie, Berlin.

Beaujardiere de la, J. (2006). **OpenGIS Web Map Server Implementation Specification**, Version 1.3.0.

Bell, B., Feiner, S. and Höllerer, T. (2001). 'View Management for Virtual and Augmented Reality', in **4th Annual ACM Symposium on User Interface Software and Technology**, pp. 101–110, Orlando. Nov 11–14.

Bénard, P., Bousseau, A. and Thollot, J. (2011). 'State-of-the-art report on temporal coherence for stylized animations', **Computer Graphics Forum**, 30/8, pp. 2367–2386.

Bertin, J. (1983). **Semiology of Graphics: Diagrams, Networks, Maps**, trans. Berg, W. J., University of Wisconsin Press, Madison.

Bratkova, M., Shirley, P. and Thompson, W. B. (2009). 'Artistic rendering of mountainous terrain', **ACM Transactions on Graphics**, 28/4, pp. 102:1–102:17.

Brewer, C. A. (1994). 'Color use guidelines for mapping and visualization', in **Visualization in Modern Cartography**, ed. by MacEachren, A.M. and Taylor, D.R.F., Ch. 7, pp. 123–147.

Brodersen, L. (2008). **Geocommunication and Information Design**, Forlaget Tankegang A/S, Frederikshavn.

Buchin, K., Sousa, M. C., Döllner, J., Samavati, F. and Walther, M. (2004). 'Illustrating Terrains using Direction of Slope and Lighting', in **4th ICA Mountain Cartography Workshop**, pp. 259–269, Vall de Nuria. Sep 30 – Oct 2.

Buchroithner, M., Schenkel, R. and Kirschenbauer, S. (2000). '3D Display techniques for cartographic purposes: semiotic aspects', **International Archives of Photogrammetry and Remote Sensing**, 33, pp. 99–106.

Cipriano, G. and Gleicher, M. (2008). 'Text Scaffolds for Effective Surface Labeling', **IEEE Transactions on Visualization and Computer Graphics**, 14/6, pp. 1675–1682.

Coconu, L., Deussen, O. and Hege, H. (2006). 'Real-Time Pen-and-Ink Illustration of Landscapes', in **4th International Symposium on Non-photorealistic Animation and Rendering**, pp. 27–35, Annecy. Jun 5–7.

Cole, F., DeCarlo, D., Finkelstein, A., Kin, K., Morley, K. and Santella, A. (2006). 'Directing Gaze in 3D Models with Stylized Focus', in **17th Eurographics Symposium on Rendering**, pp. 377–387, Nicosia. Jun 26–28.

DeCarlo, D., Finkelstein, A., Rusinkiewicz, S. and Santella, A. (2003). 'Suggestive contours for conveying shape', **ACM Transactions on Graphics**, 22/3, pp. 848–855.

Degener, P. and Klein, R. (2009). 'A variational approach for automatic generation of panoramic maps', **ACM Transactions on Graphics**, 28/1, pp. 2:1–2:14.

Deng, H., Zhang, L., Han, C., Ren, Y., Zhang, L. and Li, J. (2013). 'Efficient occlusion-free visualization for navigation in mountainous areas', **Computers & Geosciences**, 52, pp. 389–397.

Deussen, O. and Strothotte, T. (2000). 'Computer-Generated Pen-and-ink Illustration of Trees', in **27th ACM International Conference on Computer Graphics and Interactive Techniques**, pp. 13–18, New Orleans. Jul 23–28.

Döllner, J. and Baumann, K. (2000). 'Texturing Techniques for Terrain Visualization', in **11th Annual IEEE Visualization Conference**, pp. 227–234, Salt Lake City. Oct 8–13.

Döllner, J. and Buchholz, H. (2005). 'Expressive Virtual 3D City Models', in **22nd International Cartographic Conference**, A Coruña. Jul 9–16.

Döllner, J. and Walther, M. (2003). 'Real-Time Expressive Rendering of City Models', in **9th International Conference on Information Visualisation**, pp. 245–250, London. Jul 6–8.

Dowson, K. (1994). Towards Extracting Artistic Sketches and Maps from Digital Elevation Models, PhD. University of Hull.

Dykes, J. A., Moore, K. E. and Fairbairn, D. (1999). 'From Chernoff to Imhof and beyond: VRML and cartography', in **4th Symposium on The Virtual Reality Modeling Language**, pp. 99–104, Paderborn. Feb 23–26.

Elias, B., Paelke, V. and Kuhnt, S. (2005). 'Concepts for the Cartographic Visualization of Landmarks', in **3rd Symposium on LBS & TeleCartography**, pp. 149–155, Vienna. Nov 28–30.

Engel, J., Semmo, A., Trapp, M. and Döllner, J. (2013). 'Evaluating the Perceptual Impact of Rendering Techniques on Thematic Color Mappings in 3D Virtual Environments', in **18th International Workshop on Vision, Modeling and Visualization**, pp. 25–32, Lugano. Sep 11–13.

Fabrikant, S. I., Hespanha, S. R. and Hegarty, M. (2010). 'Cognitively inspired and perceptually salient graphic displays for efficient spatial inference making', **Annals of the Association of American Geographers**, 100/1, pp. 13–29.

Foerster, T., Stoter, J. E. and Kobben, B. (2007). 'Towards a Formal Classification of Generalization Operators', in **26th International Cartographic Conference**, Moscow. Aug 4–10.

Garlandini, S. and Fabrikant, S. I. (2009). 'Evaluating the effectiveness and efficiency of visual variables for geographic information visualization', in **Spatial Information Theory**, ed. by Hornsby, Kathleen Stewart and Claramunt, Christophe and Denis, Michel and Ligozat, Gérard, pp. 195–211, Springer.

Glander, T. and Döllner, J. (2009). 'Abstract representations for interactive visualization of virtual 3D city models', **Computers, Environment and Urban Systems**, 33/5, pp. 375–387.

Glander, T., Trapp, M. and Döllner, J. (2007). 'A Concept of Effective Landmark Depiction in Geovirtual 3D Environments by View-Dependent Deformation', in **4th International Symposium on LBS and TeleCartography**, Hong Kong. Nov 8–10.

Glander, T., Trapp, M. and Döllner, J. (2010). '3D Isocontours – Real-time Generation and Visualization of 3D Stepped Terrain Models', in **31st annual conference of the European Association for Computer Graphics (Shortpapers)**, pp. 17–20, Norrköping. May 3–7.

Glanville, R. S. (2004). 'Texture Bombing', in **GPU Gems**, ed. by Fernando, Randima, pp. 323–338, Boston, Addison-Wesley.

Gooch, B. and Gooch, A. (2001). **Non-Photorealistic Rendering**, AK Peters Ltd., Natick.

Götzelmann, T., Ali, K., Hartmann, K. and Strothotte, T. (2005). 'Form Follows Function: Aesthetic Interactive Labels', in **1st International Symposium on Computational Aesthetics in Graphics, Visualization, and Imaging**, pp. 193–200, Girona. May 18–20.

Grabler, F., Agrawala, M., Sumner, R. W. and Pauly, M. (2008). 'Automatic generation of tourist maps', **ACM Transactions on Graphics**, 27/3, pp. 100:1–100:11.

Häberling, C. (1999). 'Symbolization in Topographic 3D maps: Conceptual Aspects for User-Oriented Design', in **19th International Cartographic Conference**, pp. 1037–1044, Ottawa. Aug 14–21.

Häberling, C., Bär, H. and Hurni, L. (2008). 'Proposed cartographic design principles for 3D maps: a contribution to an extended cartographic theory', **Cartographica**, 43/3, pp. 175–188.

Hake, G., Grünreich, D. and Meng, L. (2002). **Kartographie: Visualisierung raum-zeitlicher Informationen**, DeGruyter, Berlin.

Hirono, D., Wu, H. Y., Arikawa, M. and Takahashi, S. (2013). 'Constrained Optimization for Disoccluding Geographic Landmarks in 3D Urban Maps', in **6th PacificVis Symposium (Pacific Visualization)**, pp. 17–24, Sidney. Feb 26 – Mar 1.

Hurni, L., Dahinden, T. and Hutzler, E. (2001). 'Digital cliff drawing for topographic maps: traditional representations by means of new technologies', **Cartographica**, 38/1, pp. 55–65.

Hurtut, T., Landes, P. E., Thollot, J., Gousseau, Y., Drouillhet, R. and Coeurjolly, J. F. (2009). 'Appearance-guided Synthesis of Element Arrangements by Example', in **7th International Symposium on**

Non-Photorealistic Animation and Rendering, pp. 51–60, New Orleans. Aug 1–2.
Imhof, E. (1975). 'Positioning names on maps', **The American Cartographer**, 2/2, pp. 128–144.
Jahnke, M., Krisp, J. M. and Kumke, H. (2013). 'Typification of Facade Elements for Virtual Three-Dimensional City Models', in **26th International Cartographic Conference**, Dresden. Aug 25–30.
Jenny, B. (2001). 'An interactive approach to analytical relief shading', **Cartographica**, 38/1, pp. 67–75.
Jenny, B., Hutzler, E. and Hurni, L. (2010a). 'Point pattern synthesis', **The Cartographic Journal**, 47/3, pp. 257–261.
Jenny, B., Hutzler, E. and Hurni, L. (2010b). 'Scree representation on topographic maps', **The Cartographic Journal**, 47/2, pp. 141–149.
Jenny, H. and Jenny, B. (2013). 'Challenges in adapting example-based texture synthesis for panoramic map creation: a case study', **Cartography and Geographic Information Science**, 40/4, pp. 297–304.
Jenny, H., Jenny, B., Cartwright, W. E. and Hurni, L. (2011). 'Interactive local terrain deformation inspired by hand-painted panoramas', **The Cartographic Journal**, 48/1, pp. 11–20.
Jenny, H., Jenny, B. and Hurni, L. (2010). 'Interactive design of 3D maps with progressive projection', **The Cartographic Journal**, 47/3, pp. 211–221.
Jobst, M. (2008a). **Ein semiotisches Modell für die kartografische Kommunikation mit 3D**, PhD. Vienna University of Technology, Institute for Geoinformation and Cartography 127/2, Vienna, pp. 152–154.
Jobst, M. and Döllner, J. (2008b). 'Better Perception of 3D-Spatial Relations by Viewport Variations', in **10th International Conference on Visual Information Systems**, pp. 7–18, Salerno. Sep 11–12.
Jobst, M., Kyprianidis, J. E. and Döllner, J. (2008c). 'Mechanisms on graphical core variables in the design of cartographic 3D city presentations', in **Geospatial Vision**, ed. by Moore, Antoni and Drecki, Igor, pp. 45–59, Springer, Berlin, HD.
Kennelly, P. J. (2012). 'Cross-hatched shadow line maps', **The Cartographic Journal**, 49/2, pp. 135–142.
Kennelly, P. J. and Kimerling, A. J. (2001). 'Modifications of Tanaka's illuminated contour method', **Cartography and Geographic Information Science**, 28/2, pp. 111–123.
Kennelly, P. J. (2009). 'Hill-shading Techniques to Enhance Terrain Maps', in **24th International Cartographic Conference**, pp. 15–21, Santiago Chile. Nov 15–21.
Kennelly, P. J. and Kimerling, A. J. (2000). 'Desktop Hachure maps from digital elevation models', **Cartographic Perspectives**, 37, pp. 78–81.
Kennelly, P. J. and Kimerling, A. J. (2006). 'Non-photorealistic rendering and terrain representation', **Cartographic Perspectives**, 54, pp. 35–54.
Kersting, O. and Döllner, J. (2002). 'Interactive 3D Visualization of Vector Data in GIS', in **10th ACM International Symposium on Advances in Geographic Information Systems**, pp. 107–112, McLean. Nov 8–9.
Kolacny, A. (1969). 'Cartographic information – a fundamental concept and term in modern cartography', **The Cartographic Journal**, 6, pp. 47–49.
Kolbe, T. H. (2009). 'Representing and Exchanging 3D City Models with CityGML', in **3D Geo-Information Sciences**, pp. 15–31, Springer, Berlin, HD.
Kraak, M. (1989). **Computer-Assisted Cartographical 3D Imaging Techniques**, Taylor & Francis, London.
Kraak, M. and Ormeling, F. (2003). **Cartography: Visualization of Geospatial Data**, Essex. Pearson Education.
Leonowicz, A. M., Jenny, B. and Hurni, L. (2010). 'Terrain sculptor: generalizing terrain models for relief shading', **Cartographic Perspectives**, 67, pp. 51–60.
Lesage, P. L. and Visvalingam, M. (2002). 'Towards sketch-based exploration of Terrain', **Computers & Graphics**, 26/2, pp. 309–328.
Levin, A., Lischinski, D. and Weiss, Y. (2004). 'Colorization using optimization', **ACM Transactions on Graphics**, 23/3, pp. 689–694.
Lorenz, H., Trapp, M., Jobst, M. and Dollner, J. (2008). 'Interactive Multi-Perspective Views of Virtual 3D Landscape and City Models', in **11th AGILE International Conference on Geographic Information Science**, pp. 301–321, Girona. Jun 13–16.
Maass, S. and Döllner, J. (2006). 'Efficient View Management for Dynamic Annotation Placement in Virtual Landscapes', in **6th International Symposium on Smart Graphics**, pp. 1–12, Vancouver. Jul 23–25.
Maass, S. and Döllner, J. (2008). 'Seamless Integration of Labels into Interactive Virtual 3D Environments Using Parameterized Hulls', in **4th International Symposium on Computational Aesthetics in Graphics, Visualization, and Imaging**, pp. 33–40, Lisbon. Jun 18–20.
MacEachren, A. (1995). **How Maps Work**, New York, Guilford Press.
McMaster, R. B. and Shea, S. K. (1992). **Generalization in digital cartography**, Technical report, Washington, D.C., USA.
Merian, M. (2005). **Topographia Germaniae**, Archiv Verlag, Braunschweig.
Montello, D. R. (2002). 'Cognitive map-design research in the twentieth century: theoretical and empirical approaches', **Cartography and Geographic Information Science**, 29/3, pp. 283–304.
Mower, J. E. (2011). 'Supporting automated pen and ink style surface illustration with B-Spline Models', **Cartography and Geographic Information Science**, 38/2, pp. 174–183.
Nienhaus, M. and Döllner, J. (2003). 'Edge-enhancement – an algorithm for real-time non-photorealistic rendering', **Journal of WSCG**, 11/2, pp. 346–353.
Nivala, A. M. and Sarjakoski, L. T. (2003). 'Need for Context-Aware Topographic Maps in Mobile Devices', in **9th Scandinavian Research Conference on Geographical Information Science**, pp. 15–29, Espoo. Jun 4–6.
Pasewaldt, S., Semmo, A., Trapp, M. and Döllner, J. (2014). 'Multi-perspective 3D panoramas', **International Journal of Geographical Information Science**, 28/10, pp. 2030–2051.
Patterson, T. and Kelso, N. V. (2004). 'Hal shelton revisited: designing and producing natural-color maps with satellite land cover data', **Cartographic Perspectives**, 47, pp. 28–55.
Pegg, D. (2012). Design Issues with 3D Maps and the Need for 3D Cartographic Design Principles. http://lazarus.elte.hu/cet/academic/pegg.pdf [Accessed 30 March 2015].
Peterson, M. P. (2005). **Interactive and Animated Cartography**, Prentice Hall, Upper Saddle River.
Petrovic, D. (2003). 'Cartographic Design in 3D Maps', in **21st International Cartographic Conference**, pp. 10–16, Durban. Aug 10-16.
Pfautz, J. D. (2000). **Depth Perception in Computer Graphics**, PhD. University of Cambridge, Cambridge.
Qu, H., Wang, H., Cui, W., Wu, Y. and Chan, M. Y. (2009). 'Focus+Context Route Zooming and Information Overlay in 3D Urban Environments', **IEEE Transactions on Visualization and Computer Graphics**, 15/6, pp. 1547–1554.
Reichenbacher, T. and Swienty, O. (2007). 'Attention-Guiding Geovisualisation', in **10th AGILE International Conference on Geographic Information Science**, pp. 8–11, Aalborg. May 8–11.
Ropinski, T., Praßni, J. S., Roters, J. and Hinrichs, K. (2007). 'Internal Labels as Shape Cues for Medical Illustration', in **12th International Workshop on Vision, Modeling, and Visualization**, pp. 203–212, Saarbrücken. Nov 7–9.
Saito, T. and Takahashi, T. (1990). 'Comprehensible Rendering of 3-D Shapes', in **17th International ACM Conference on Computer Graphics and Interactive Techniques**, pp. 197–206, Dallas. Aug 6–10.
Samsonov, T. (2014). 'Morphometric mapping of topography by flowline hachures', **The Cartographic Journal**, 51/1, pp. 63–74.
Santella, A. and DeCarlo, D. (2004). 'Visual Interest and NPR: an Evaluation and Manifesto', in **3rd International Symposium on Non-Photorealistic Animation and Rendering**, pp. 71–150, Annecy. Jun 7–9.
Schneider, M. and Klein, R. (2007). 'Efficient and accurate rendering of vector data on virtual landscapes', **Journal of WSCG**, 15/1–3, pp. 59–66.
Semmo, A. and Döllner, J. (2014). 'Image Filtering for Interactive Level-of-Abstraction Visualization of 3D Scenes', in **10th International Symposium on Computational Aesthetics**

in Graphics, Visualization, and Imaging, pp. 5–14, Vancouver. Aug 8–10.

Semmo, A., Hildebrandt, D., Trapp, M. and Döllner, J. (2012a). 'Concepts for cartography-oriented visualization of virtual 3D city models', **Photogrammetrie–Fernerkundung–Geoinformation**, 4, pp. 455–465.

Semmo, A., Trapp, M., Kyprianidis, J. E. and Döllner, J. (2012b). 'Interactive visualization of generalized virtual 3D city models using level-of-abstraction transitions', **Computer Graphics Forum**, 31/3, pp. 885–894.

Semmo, A., Kyprianidis, J. E., Trapp, M. and Döllner, J. (2013). 'Real-Time Rendering of Water Surfaces with Cartography-Oriented Design', in **9th International Symposium on Computational Aesthetics in Graphics, Visualization, and Imaging**, pp. 5–14, Anaheim. Jul 19–20.

Sester, M. (2007). '3D Visualization and Generalization', in **51st Photogrammetric Week**, pp. 285–295, Stuttgart. Sep 3–7.

Surdick, R. T., Davis, E. T., King, R. A., Corso, G. M., Shapiro, A., Hodges, L. and Elliot, K. (1994). 'Relevant Cues for the Visual Perception of Depth: Is Where You See it Where it is?', in **Proceedings of the Human Factors and Ergonomics Society Annual Meeting**, Volume 38, Issue 19, pp. 1305–1309.

Takahashi, S., Yoshida, K., Shimada, K. and Nishita, T. (2006). 'Occlusion-free animation of driving routes for car navigation systems', **IEEE Transactions on Visualization and Computer Graphics**, 12/5, pp. 1141–1148.

Trapp, M., Beesk, C., Pasewaldt, S. and Döllner, J. (2010). 'Interactive Rendering Techniques for Highlighting in 3D Geovirtual Environments', in **5th 3D GeoInfo Conference**, pp. 197–210, Berlin. Nov 3–4.

Trapp, M., Glander, T., Buchholz, H. and Döllner, J. (2008). '3D Generalization Lenses for Interactive Focus + Context Visualization of Virtual City Models', in **12th International Conference on Information Visualisation**, pp. 356–361, London. Jul 9–11.

Tufte, E. R. (1983). **The Visual Display of Quantitative Information**, Volume 2. Graphics press, Cheshire, CT.

Tyner, J. (2010). **Principles of map design**, New York, Guilford Press.

Vaaraniemi, M., Treib, M. and Westermann, R. (2011). 'High-quality cartographic roads on high-resolution DEMs', **Journal of WSCG**, 12/2, pp. 41–48.

Vaaraniemi, M., Freidank, M. and Westermann, R. (2013). 'Enhancing the Visibility of Labels in 3D Navigation Maps', in **Progress and New Trends in 3D Geoinformation Sciences**, pp. 23–40, Springer, Berlin.

Vaaraniemi, M., Görlich, M. and in der Au, A. (2014). 'Intelligent prioritization and filtering of labels in navigation maps', **Journal of WSCG**, 22/1, pp. 11–20.

Vázquez, P. P., Feixas, M., Sbert, M. and Heidrich, W. (2004). 'Automatic view selection using viewpoint entropy and its application to image-based modeling', **Computer Graphics Forum**, 22/4, pp. 689–700.

Ware, C. (2004). **Information Visualization: Perception for Design**, Morgan Kaufmann Publishers Inc., San Francisco.

Wartell, Z., Kang, E., Wasilewski, T., Ribarsky, W. and Faust, N. (2003). 'Rendering Vector Data over Global, Multi-resolution 3D Terrain', in **Symposium on Data Visualisation**, pp. 213–222, Grenoble. May 26–28.

Whelan, J. C. and Visvalingam, M. (2003). 'Formulated Silhouettes for Sketching Terrain', in **1st Theory and Practice of Computer Graphics Conference**, pp. 90–96, Birmingham. Jun 3–5.

Yoeli, P. (1985). 'Topographical relief depiction by hachures with computer and plotter', **The Cartographic Journal**, 22/2, pp. 111–124.